PLASMA LAMP WITH DIELECTRIC WAVEGUIDE

CROSS- REFERENCE TO RELATED APPLICATIONS

[0001] ~~[0001]~~ This application is a continuation of U.S. application Ser. No. 09/809,718 ("718") filed on Mar. 15, 2001, entitled "Plasma Lamp With Dielectric Waveguide," which claims priority to U.S. provisional application Ser. No. 60/222,028 filed on Jul. 31, ~~2000,~~2000 entitled "Plasma Lamp." Applications 09/809,718 and 60/222,028 are ~~hereby~~ incorporated herein by reference.

BACKGROUND OF THE INVENTION

~~[0002] 1.~~ **Field of the Invention**

[0002] ~~[0003]~~ The field of the present invention relates to devices and methods for generating light, and more particularly to electrodeless plasma lamps.

~~[0004] 2. Related Art~~

Background

[0003] ~~[0005]~~ Electrodeless plasma lamps provide point-like, bright, white light sources. Because they do not use electrodes, electrodeless plasma lamps often have longer useful lifetimes than other lamps. Electrodeless plasma lamps in the ~~related~~prior art have certain common features. For example in U.S. ~~Pat.~~Patent Nos. 4,954,755 to Lynch et al., 4,975,625 to Lynch et al., 4,978,891 to Ury et al., 5,021,704 to Walter et al., 5,448,135 to Simpson, 5,594,303 to Simpson, 5,841,242 to Simpson et al., 5,910,710 to Simpson, and 6,031,333 to Simpson, each of which is incorporated herein by reference, the plasma lamps direct microwave energy into an air cavity, with the air cavity enclosing a bulb containing a mixture of substances that can ignite, form a plasma, and emit light.

[0004] ~~[0006]~~ The plasma lamps described in these ~~references~~patents are intended to provide brighter light sources with longer life and more stable ~~spectra~~spectrum than electrode lamps. However, for many applications, light sources that are brighter, smaller, less expensive, more reliable, and have long useful lifetimes are desired, but such light sources until now have been unavailable. Such applications include, for example, streetlights and emergency response vehicles. A need exists~~,~~ therefore, for a very bright, durable light source at low cost.

[0005] ~~[0007]~~ In the ~~related~~prior art, the air-filled cavity of ~~an~~the electrodeless plasma lamp is typically ~~is~~ constructed in part by a metal mesh. Metal mesh is used because it contains the microwave energy within the cavity while at the same time permitting the maximum amount of visible light to escape. The microwave energy is typically generated by a magnetron or solid state electronics and is guided into the cavity through one or more waveguides. Once in the air-filled cavity, microwave energy of select frequencies resonates, where the actual frequencies that resonate depend upon the shape and size of the cavity. Although there is tolerance in the frequencies that may be used to power the lamps, in practice, the power sources are limited to microwave frequencies in the range of 1-10 GHz.

[0006] ~~[0008]~~ Because of the need to establish a resonance condition in the air-filled cavity, the cavity generally may not be smaller than one-half the wavelength of the microwave energy used to power the lamp. The air-filled cavity and thereby, the plasma lamp itself has a lower limit on its size. However, for many applications, such as for high-resolution monitors, bright lamps, and projection TVs, these sizes remain prohibitively large. A need exists therefore for a plasma lamp that is not constrained to the minimum cavity sizes ~~of~~illustrated by the ~~related~~prior art.

[0007] ~~[0009]~~ In the ~~related~~prior art, ~~a bulb~~the bulbs are typically ~~is~~ positioned at a point in the cavity where the electric field created by the microwave energy is at a maximum. The support structure for ~~a~~the bulb is preferably ~~is~~ of a size and composition that does not interfere with the resonating microwaves, as any interference with the microwaves reduces the efficiency of the lamp. The bulbs, therefore, are typically ~~are~~ made from quartz. Quartz bulbs, however, are prone to failure because the plasma temperature can be several thousand degrees centigrade, which can bring the quartz wall temperature to near 1000°°C. Furthermore, quartz bulbs are unstable in terms of mechanical stability and optical and electrical properties over long periods. A need exists, therefore, for a light source that overcomes the above--described issues, but that is also stable in its spectral characteristics over long periods.

[0008] ~~[0010]~~ In prior art plasma lamps ~~of the related art~~, the bulb typically contains a noble gas combined with a light emitter, a second element or compound which typically comprises sulfur, selenium, a compound containing sulfur or selenium, or any one of a

number of metal halides. Exposing the contents of the bulb to microwave energy of high intensity causes the noble gas to become a plasma. The free electrons within the plasma excite the light emitter within the bulb. When the light emitter returns to a lower electron state, radiation is emitted. The spectrum of light emitted depends upon the characteristics of the light emitter within the bulb. Typically, the light emitter is chosen to cause emission of visible light.

[0009] ~~[0011]~~ Plasma lamps of the type described above frequently require high intensity microwaves to initially ignite the noble gas into plasma. However, over half of the energy used to generate and maintain the plasma is typically ~~is~~ lost as heat, making heat dissipation a problem. Hot spots can form on the bulb causing spotting on the bulb and thereby reducing the efficiency of the lamp. Methods have been proposed to reduce the hot spots by rotating the lamp to better distribute the plasma within the lamp and by blowing constant streams of air at the lamp. These solutions, however, add structure to the lamp, thereby increasing its size and cost. Therefore, a need exists for a plasma lamp that requires less energy to ignite and maintain the plasma, and includes a minimum amount of additional structure for efficient dissipation of heat.

~~BRIEF~~ SUMMARY OF THE INVENTION

~~[0012] This invention provides distinct advantages over the electrodeless plasma lamps in the related art, such as brighter and spectrally more stable light, greater energy efficiency, smaller overall lamp sizes, and longer useful life spans. Rather than using a waveguide with an air-filled resonant cavity, embodiments of the invention use a waveguide having a body consisting essentially of at least one dielectric material having a dielectric constant greater than approximately 2. Such dielectric materials include solid materials such as ceramics, and liquid materials such as silicone oil. A larger dielectric constant permits "dielectric waveguides" to be significantly smaller than waveguides of the related art, enabling their use in many applications where the smallest size achievable heretofore has made such use impossible or impractical.~~

~~[0013] In one aspect of the invention, a lamp includes a waveguide having a body comprising at least one dielectric material and having at least one surface determined by a waveguide outer surface. Each material has a dielectric constant greater than approximately 2. The lamp further includes a first microwave probe positioned within and in intimate contact with the body, adapted to couple microwave energy into the body from a microwave source having an output and an input and operating within a frequency range from about 0.5 to about 30 GHz at a preselected frequency and intensity. The probe is connected to the source output. The frequency and intensity and the body shape and dimensions are selected so that the body resonates in at least one resonant mode having at least one electric field maximum. The lamp further includes at least one lamp chamber depending, respectively, from at least one waveguide outer surface into the body, with each chamber at a location corresponding to an electric field maximum during operation. The lamp further includes a gas-fill in each chamber which when receiving microwave energy from the resonating body forms a light-emitting plasma.~~

~~[0014] In another aspect of the invention, a lamp includes a waveguide having a body with a main portion including a solid dielectric material and a body first side, and a protrusion extending from the first side and terminating in a second side determined by a waveguide outer surface from which depends a lamp chamber into the protrusion. The lamp further includes a microwave probe positioned within and in intimate contact with the body main portion, adapted to couple microwave energy into the main portion from a microwave source having an output and an input and operating within a frequency range from about 0.5 to about 30 GHz at a preselected frequency and intensity. The probe is connected to the source output. The frequency~~

~~and intensity and the body main portion shape and dimensions are selected such that the main portion resonates in at least one resonant mode having at least one electric field maximum. The lamp further includes a bulb envelope substantially within the chamber, containing a gas-fill which when receiving microwave energy from the resonating body main portion forms a light-emitting plasma.~~

~~**[0015]** In still another aspect of the invention, a lamp includes a waveguide having a body including a solid dielectric material and a side determined by a waveguide outer surface from which depends a lamp chamber. The chamber aperture is circumscribed by a bulb support structure sealed to the outer surface. The lamp further includes a microwave probe positioned within and in intimate contact with the body, adapted to couple microwave energy into the body from a microwave source having an output and an input and operating within a frequency range from about 0.5 to about 30 GHz at a preselected frequency and intensity. The probe is connected to the source output. The frequency and intensity and the body shape and dimensions are selected such that the body resonates in at least one resonant mode having at least one electric field maximum. The lamp further includes a self-enclosed bulb substantially within the chamber and hermetically sealed to the bulb support structure. The bulb contains a gas-fill which when receiving microwave energy from the resonating body main portion forms a light-emitting plasma.~~

~~**[0016]** In yet another aspect of the invention, a method for producing light includes the step of coupling microwave energy into a waveguide having a body including at least one dielectric material and having at least one surface determined by a waveguide outer surface from which~~

~~depends at least one lamp chamber into the body. Each material has a dielectric constant greater than approximately 2. The energy frequency and intensity and the body shape and dimensions are selected such that the body resonates in a least one resonant mode having at least one electric field maximum. The method further includes the step of directing resonant microwave energy into the lamp chamber(s), with each lamp chamber containing a gas-fill including a plasma-forming gas and a light emitter. The method further includes the step of creating a plasma by interacting the resonant energy with the gas-fill, thereby causing emission of light.~~

[0010] This invention generally provides, in one aspect, devices and methods of producing bright, spectrally stable light.

[0011] In accordance with one embodiment as described herein, a device for producing light comprises an electromagnetic energy source, a waveguide having a body formed of a dielectric material, and a bulb. Preferably, the waveguide is connected to the energy source for receiving electromagnetic energy from the energy source. The waveguide builds and contains the electromagnetic energy. The bulb, which is coupled to the waveguide, receives electromagnetic energy from the waveguide. The received electromagnetic energy ignites a gas-fill that forms a plasma and emits light, preferably in the visible spectral range.

[0012] In one preferred embodiment, the bulb is shaped to reflect light outwards through its window. The electromagnetic energy source is preferably a microwave energy source that is efficiently coupled to and preferably thermally isolated from the waveguide. Furthermore, the outer surface of the waveguide, preferably with the exception of the bulb cavity, is coated with a material to contain the microwave energy within the waveguide. The dielectric forming the waveguide preferably has a high dielectric constant, a high dielectric strength, and a low loss tangent. This permits high power densities within the waveguide. A heat sink preferably is attached to the outer surfaces of the waveguide to dissipate heat.

[0013] In accordance with a first alternative embodiment, the lamp is operated in resonant cavity mode. In this mode, the microwave energy directed into the waveguide has a frequency such that it resonates within the waveguide. The microwave feed and the

bulb are preferably positioned at locations with respect to the waveguide that correspond to electric field maxima of the resonant frequency.

[0014] In accordance with a second alternative embodiment, the lamp is operated in a dielectric oscillator mode. In this mode, an energy feedback mechanism or probe is coupled to the dielectric waveguide at a point that in one embodiment corresponds to an energy maximum. The probe senses the electric field amplitude and phase within the waveguide at the point of coupling. Using the probe signal to provide feedback, the lamp may be continuously operated in resonant cavity mode, even if the resonant frequency changes as the plasma forms in the bulb and/or if the dielectric waveguide undergoes thermal expansion due to the heat generated. The probe provides feedback to the microwave source and the microwave source adjusts its output frequency to dynamically maintain a resonance state.

[0015] Further embodiments, variations and enhancements, including combinations of the above-described embodiments, or features thereof, are also described herein or depicted in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] ~~[0017]~~ FIG. 1 illustrates a sectional view of a ~~dielectric waveguide integrated plasma lamp (DWIPL) including a waveguide having a body consisting essentially of a solid dielectric material, integrated with a bulb envelope containing a light-emitting plasma~~plasma lamp according to a preferred embodiment.

[0017] ~~[0018] FIGs~~FIGS. 2A and 2B illustrate sectional views of alternative embodiments of a ~~DWIPL.~~ plasma lamp.

[0018] ~~[0019] FIGs~~FIGS. 3A and 3B illustrate a sectional view of an alternative embodiment of a ~~DWIPL~~plasma lamp wherein ~~a self-enclosed~~the bulb is thermally isolated from the dielectric waveguide.

[0019] ~~[0020] FIGs~~FIGS. 4A-D illustrate different resonant modes within a rectangular prism~~-~~-shaped ~~dielectric~~ waveguide.

[0020] ~~[0021] FIGs~~FIGS. 5A-C illustrate different resonant modes within using a cylindrical prism-shaped ~~dielectric~~cylindrical waveguide.

[0021] ~~[0022]~~ FIG. 6 illustrates ~~a DWIPL~~an embodiment ~~wherein~~of the apparatus using a feedback mechanism ~~provides information to a~~to provide feedback to the microwave

source ~~from a probe probing the waveguide field, thereby dynamically maintaining~~to maintain a resonant mode ~~within the waveguide~~of operation.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0022] ~~[0023]~~ Turning now to the drawings, FIG. 1 illustrates a preferred embodiment of a dielectric waveguide integrated plasma lamp 101 (DWIPL) ~~101~~. The DWIPL 101 ~~includes~~preferably comprises a source 115 of electromagnetic radiation, preferably microwave radiation, a waveguide 103 having a body ~~104~~ formed of a ~~solid~~ dielectric material, and a ~~microwave probe~~feed 117 coupling the radiation source 115 to the waveguide 103. ~~Waveguide **103** is determined by opposed sides **103A**, **103B**, and opposed sides **103C**, **103D** generally transverse to sides **103A**, **103B**.~~ As used herein, the term "waveguide" generally refers to any device having a characteristic and purpose of at least partially confining electromagnetic energy. ~~As used herein, the term "dielectric waveguide" refers to a waveguide having a body consisting essentially of at least one dielectric material having a dielectric constant greater than approximately 2. As used herein, the term "probe" is synonymous with "feed" in the '718 application.~~ The DWIPL 101 further includes a bulb 107, ~~disposed proximate to side **103A** and preferably generally opposed to probe **117**, containing a gas-fill **108** including~~that is preferably disposed on an opposing side of the waveguide 103, and contains a gas-fill, preferably comprising a noble gas and a light emitter, which when receiving ~~microwave~~electromagnetic energy at a ~~predetermined operating~~specific frequency and intensity forms a plasma and emits light. ~~As used herein, the term "ignition" means initial breakdown of atoms or molecules of the initially neutral gas-fill into ions. As used herein, the term "bulb" refers to an enclosure disposed substantially if not totally within a lamp chamber in a waveguide body, which either is a "bulb envelope," viz., an enclosure determined by a surrounding wall and a window covering the chamber aperture and hermetically sealed to the wall, or is a self-enclosed discrete bulb within the chamber. The term "bulb cavity," where used herein, refers to the combination of a lamp chamber and a discrete bulb disposed within the chamber. Because the gas-fill is confined to a discrete bulb, a bulb cavity need not be hermetically sealed.~~

[0023] ~~[0024] Source **115** provides~~In a preferred embodiment, the microwave radiation source 115 feeds the waveguide 103 microwave energy ~~to waveguide **103**~~ via ~~probe~~the

feed 117. The waveguide contains and guides the ~~energy to an enclosed lamp chamber 105, depending from side 103A into body 104, in which is disposed~~microwave energy to a cavity 105 preferably located on an opposing side of the waveguide 103 from the feed 117. Disposed within the cavity 105 is the bulb 107 containing the gas-fill. Microwave energy is preferably directed into the enclosed cavity 105, and in turn the bulb 107. This microwave energy generally frees electrons from ~~noble gas atoms,~~their normal state and thereby ~~creating~~transforms the noble gas into a plasma. The free electrons of the noble gas excite the light emitter. ~~De~~The de-excitation of the light emitter results in the emission of light. As will become apparent, the ~~DWIPL~~different embodiments of DWIPLs disclosed herein offer distinct advantages over the plasma lamps in the ~~related~~prior art, such as an ability to produce brighter and spectrally more stable light, greater energy efficiency, smaller overall lamp sizes, and longer useful life spans.

[0024] ~~[0025]~~ The microwave source 115 in FIG. 1 is shown schematically as solid state electronics~~;~~, however, other devices commonly known in the art ~~operating~~that can operate in the 0.5 - 30 GHz range may also be used as a microwave source, including but not limited to klystrons and magnetrons. The preferred ~~operating frequency~~ range for the microwave source ~~115~~ is from about 500 MHz to about 10 GHz.

[0025] ~~[0026]~~ Depending upon the heat sensitivity of the microwave source 115, the microwave source 115 may be thermally isolated from the bulb 107, which during operation ~~typically~~preferably reaches temperatures between about 700° °C and about 1000° °C. Thermal isolation of the bulb 107 from the source 115 provides a benefit of avoiding degradation of the source ~~due to heating.~~115. Additional thermal isolation of the microwave source 115 may be accomplished by any one of a number of methods commonly known in the art, including but not limited to using an insulating material or vacuum gap occupying an optional space 116 between the source 115 and waveguide 103. If the ~~space 116~~latter option is ~~included~~chosen, appropriate microwave ~~probes~~feeds are used to couple the microwave source 115 to the waveguide 103.

[0026] ~~[0027]~~ In FIG. 1, ~~probe~~ the feed 117 that transports ~~microwave energy~~microwaves from the source 115 to the waveguide 103 preferably ~~is~~comprises a coaxial probe. However, any one of several different types of microwave ~~probes~~feeds commonly known in the art may be used, such as microstrip lines or fin line structures.

[0027] ~~[0028]~~ Due to mechanical and other considerations such as heat, vibration, aging ~~and~~, or shock, when feeding microwave ~~energy~~signals into ~~the~~a dielectric material, contact between the ~~probe~~feed 117 and the waveguide 103 is preferably ~~is~~ maintained using a positive contact mechanism 121. The contact mechanism 121 provides ~~a~~ constant pressure ~~by~~between the ~~probe on~~feed 117 and the waveguide 103 to minimize the ~~possibility~~probability that microwave energy will be reflected back through the ~~probe rather than entering~~feed 117 and not transmitted into the waveguide~~.~~ 103. In providing constant pressure, the contact mechanism 121 compensates for small dimensional changes in the ~~probe~~microwave feed 117 and the waveguide 103 that may occur due to thermal heating or mechanical shock. ~~Contact~~The contact mechanism ~~121~~ may be a spring loaded device, such as is illustrated in FIG. 1, a bellows type device, or any other device commonly known in the art that can sustain a constant pressure for continuously and steadily transferring microwave energy.

[0028] ~~[0029]~~ When coupling ~~probe~~the feed 117 to the waveguide 103, intimate contact is preferably ~~is~~ made by depositing a metallic material 123 directly on the waveguide 103 at its point of contact with the ~~probe. This~~feed 117. The metallic material 123 eliminates gaps that may disturb the coupling~~,~~ and is preferably ~~includes~~comprised of gold, silver, or platinum, although other conductive materials may also be used. The metallic material 123 may be deposited using any one of several methods commonly known in the art, such as depositing the metallic material 123 as a liquid and then firing it in an oven to provide a solid contact.

[0029] ~~[0030]~~ In FIG. 1, the waveguide 103 is ~~in~~preferably the shape of a rectangular prism~~. However~~, however, the waveguide 103 may also have a cylindrical prism shape, a sphere-like shape, or any other shape ~~that can efficiently guide microwave energy from the probe 117 to the bulb 107,~~, including a complex, irregular shape ~~whose~~the resonant frequencies of which are preferably ~~are~~ determined ~~using~~through electromagnetic ~~theory~~ simulation tools~~.~~, that can efficiently guide microwave energy from the feed 117 to the bulb 107. The actual dimensions of the waveguide ~~will~~may vary depending upon the ~~microwave operating~~ frequency of the microwave energy used and the dielectric constant of the body of waveguide ~~body 104.~~103.

[0030] ~~[0031]~~ In one preferred embodiment, the waveguide body ~~104 has a volume of~~is approximately 12,500 mm^3 ~~and~~with a dielectric constant of approximately ~~9,~~9 and ~~the~~ operating frequency ~~is~~of approximately 2.4 GHz. Waveguide bodies ~~of~~on this scale are significantly smaller than the waveguides in the plasma lamps of the ~~related~~prior art. ~~Thus~~As such, the waveguides ~~according to the present invention~~in the preferred embodiments represent a significant advance over the ~~related~~prior art because ~~their~~the smaller size allows ~~them~~the waveguide to be used in many applications ~~where the smallest size achievable heretofore has precluded or made~~, where waveguide size had previously prohibited such use or made such use wholly impractical ~~such use. By using materials with~~. For larger dielectric constants, even smaller sizes ~~can~~for the waveguides may be achieved. Besides the obvious advantages ~~provided~~created by ~~smaller~~a reduction in size, size reduction translates into a higher power density ~~and~~, lower loss, and thereby ~~making~~, an ease in igniting the lamp ~~ignition easier~~.

[0031] ~~[0032]~~ Regardless of its shape and size, the waveguide ~~body 104~~103 preferably ~~includes a solid~~has a body comprising a dielectric material ~~having~~which, for example, preferably exhibits the following properties: (1) a dielectric constant preferably greater than approximately 2; (2) a loss tangent preferably less than approximately 0.01; (3) a thermal shock resistance quantified by a failure temperature of preferably greater than approximately 200°°C; (4) a DC breakdown threshold of preferably greater than approximately 200 kilovolts/inch; (5) a coefficient of thermal expansion of preferably less than approximately 10^{-5}/°°C; ,(6) a zero or slightly negative temperature coefficient of the dielectric constant; (7) ~~stoichiometric~~stoichemetric stability over a preferred range of temperature ~~range of~~, preferably from about –80° °C to about 1000° °C~~;~~, and (8) a thermal conductivity of preferably approximately 2 W/mK (watts per milliKelvin).

[0032] ~~[0033]~~ Certain ceramics, including alumina, zirconia, titanates, and ~~variations~~variants or combinations of these materials, and silicone oil may satisfy many of the above preferences, and may be used because of their electrical and thermo-mechanical properties. ~~Alternatively, the dielectric material may be a silicone oil. Preferably, body 104 has a substantial thermal mass which aids efficient distribution and dissipation of heat and provides thermal isolation between source 115 and bulb 107.~~ In

any event, it should be noted that the embodiments presented herein are not limited to a waveguide exhibiting all or even most of the foregoing properties.

[0033] In the various embodiments of the waveguide disclosed herein, such as in the example outlined above, the waveguide preferably provides a substantial thermal mass, which aids efficient distribution and dissipation of heat and provides thermal isolation between the lamp and the microwave source.

[0034] ~~[0034] Referring to **FIG. 2A**, a DWIPL **200** includes a waveguide **203** having a body **204** consisting essentially of a solid dielectric material, and a side **203A** with an enclosed lamp chamber **205** depending from side **203A** into body **204**. A bulb **207** is disposed within the chamber. DWIPL **200** further includes a microwave probe **209** generally opposed to chamber **205**. Preferably, bulb **207** is in the same plane as probe~~Alternative embodiments of DWIPLS 200, 220 are depicted in FIGS. 2A-B. In FIG. 2A, a bulb 207 and bulb cavity 205 are provided on one side of a waveguide 203, preferably on a side opposite a feed 209, and more preferably in the same plane as the feed 209, where the electric field of the microwave energy is at a maximum. Where more than one maximum of the electric field is ~~present~~provided in the waveguide 203, the ~~chamber and~~ bulb ~~are~~207 and bulb cavity 205 may be positioned at one maximum and the ~~probe~~feed 209 at another maximum. By placing the ~~probe~~feed 209 and bulb ~~at~~207 at a maximum for the electric field ~~maxima~~, ~~the amount of energy transferred into the bulb is maximized.~~a maximum amount of energy is respectively transferred and intercepted. The bulb cavity 205 is a concave form in the body of the waveguide 203.

[0035] ~~[0035] Referring to **FIG. 2B**, a DWIPL **220** includes a waveguide **223** having a body **224** with a main portion **224A** consisting essentially of a solid dielectric material. Body **224** further includes a convexly-shaped portion **224B** which protrudes outwardly from portion **224A** to form an enclosed lamp chamber **225**. As in DWIPL **200**, a~~As shown in FIG. 2B, the body of the waveguide 223 optionally protrudes outwards in a convex form, from the main part of the body of the waveguide 203 to form the bulb cavity 225. As in FIG. 2A, in FIG. 2B, the bulb 227 ~~disposed within chamber 225~~ is preferably positioned ~~generally opposed to a microwave probe 221. In contrast to DWIPL 200, bulb~~ opposite to the feed 221. However, where more than one electric field maximum is provided in the waveguide 203, the bulb 207, 227 may be positioned in a

plane other than the plane of ~~probe 221 where more than one maximum of the electric field is present in waveguide 223.~~the feed 209, 221.

[0036] ~~[0036]~~ Returning to FIG. 1, ~~sides 103A, 103B, 103C, 103D of~~the outer surfaces of the waveguide 103, with the exception of those surfaces ~~depending from side 103A into body 104 which form lamp chamber 105, are~~forming the bulb cavity 105, are preferably coated with a thin metallic coating 119 ~~which reflects~~to reflect the microwaves ~~in the operating frequency range~~. The overall reflectivity of the coating 119 determines the level of energy contained within the waveguide~~.~~ 103. The more energy that can be stored within the waveguide~~,~~ 103, the greater the overall efficiency of the lamp 101. ~~Preferably,~~The coating 119 also preferably suppresses evanescent radiation leakage~~and~~. In general, the coating 119 preferably significantly ~~attenuates~~eliminates any stray microwave field~~(s)~~.

[0037] ~~[0037]~~ Microwave leakage from ~~chamber~~the bulb cavity 105 ~~is~~may be significantly attenuated by ~~choosing the chamber dimensions to be~~having a cavity 105 that is preferably significantly smaller than the ~~wavelength(s) of the microwaves~~microwave wavelengths used to operate the lamp 101. For example, the length of the diagonal ~~of a~~for the window ~~sealing the chamber should be~~is preferably considerably less than half of the microwave wavelength (in free space) used.

[0038] ~~[0038] Still referring to FIG. 1,~~The bulb 107 ~~includes~~is disposed within the bulb cavity 105, and preferably comprises an outer wall 109 ~~having an inner surface 110,~~ and a window 111. ~~Alternatively, the lamp chamber wall~~In one preferred embodiment, the cavity wall of the body of the waveguide 103 acts as the outer wall of the bulb~~.~~ 107. The components of the bulb 107 preferably include ~~at least one~~ one or more dielectric ~~material~~materials, such as ~~a ceramic or sapphire~~ceramics and sapphires. In one embodiment, the ~~ceramic~~ceramics in the bulb ~~is~~are the same as the material used in ~~body 104.~~waveguide 103. Dielectric materials are preferred for the bulb 107 because the bulb 107 is preferably ~~is~~ surrounded by the dielectric body ~~104,~~of the waveguide 103 and the dielectric materials ~~facilitate~~help ensure efficient coupling of the microwave energy with the gas-fill ~~108~~ in the bulb~~.~~ 107.

[0039] ~~[0039] In FIG. 1,~~The outer wall 109 is preferably coupled to the window 111 using a seal 113, thereby ~~determining~~defining a bulb envelope 127 which contains the

gas-fill ~~108.~~comprising the plasma-forming gas and light emitter. The plasma-forming gas is preferably ~~is~~ a noble gas, which enables the formation of a plasma. The light emitter is preferably ~~is~~ a vapor formed of any one of a number of elements or compounds currently known in the art, such as sulfur, selenium, a compound containing sulfur or selenium, or ~~a~~any one of a number of metal ~~halide~~halides, such as indium bromide ($InBr_3$).

[0040] ~~[0040] To confine~~To assist in confining the gas-fill within the bulb ~~envelope,~~107, the seal 113 preferably ~~is~~comprises a hermetic seal. ~~Outer~~The outer wall 109 preferably ~~includes~~comprises alumina because of its white color, temperature stability, low porosity, and ~~coefficient of~~ thermal expansion coefficient. However, other materials that generally provide one or more of these properties may be used. ~~Preferably,~~The outer wall 109 is also preferably contoured to ~~maximize the~~reflect a maximum amount of light ~~reflected~~ out of ~~chamber~~the cavity 105 through the window 111. For instance, the outer wall 109 may have a parabolic contour~~.~~ to reflect light generated in the bulb 107 out through the window 111. However, other outer wall contours or configurations that facilitate directing light out through the window 111 may be used.

[0041] ~~[0041] Window~~The window 111 preferably ~~includes~~comprises sapphire for ~~high~~ light ~~transmissivity~~transmittance and because its ~~coefficient of~~ thermal expansion coefficient matches well with ~~that of~~ alumina. ~~Alternatively, other~~Other materials ~~having~~that have a similar light transmittance and thermal expansion ~~properties~~coefficient may be used~~. Alternatively,~~ for the window 111. In an alternative embodiment, the window 111 ~~includes~~may comprise a lens to collect the emitted light.

[0042] ~~[0042]~~ As referenced above, during operation, the bulb 107 may reach temperatures of up to about 1000º °C. Under such conditions, ~~body 104~~the waveguide 103 in one embodiment acts as a heat sink for the bulb~~.~~ 107. By reducing the heat load and heat-induced stress ~~on~~upon the various ~~elements~~components of the DWIPL 101, the ~~lamp's~~ useful life span ~~can be~~of the DWIPL 101 is generally increased beyond the life span of typical electrodeless lamps ~~in the related art. As shown in **FIG. 1**, effective~~. Effective heat dissipation may be obtained by ~~attaching a plurality of~~preferably placing heat-sinking fins 125 ~~to sides **103A**, **103C** and **103D**. In DWIPL **220** (see **FIG. 2B**),~~

~~lamp chamber **225** extends away from the main portion **224A** of body **224**, allowing heat to be removed efficiently by placing a plurality of~~around the outer surfaces of the waveguide 103, as depicted in FIG. 1. In the embodiment shown in FIG. 2B, with the cavity 225 extending away from the main part of the body of the waveguide 223, the DWIPL 220 may be used advantageously to remove heat more efficiently by placing fins 222 ~~proximate to~~in closer proximity to the bulb 227.

[0043] ~~[0043] Alternatively,~~In another embodiment, the body of the waveguide ~~body **104** includes~~103 comprises a dielectric, such as a titanate, which is generally ~~is unstable~~not stable at high ~~temperature~~temperatures. In ~~such embodiments~~this embodiment, the waveguide 103 is preferably ~~is~~ shielded from the heat generated in the bulb 107 by ~~interposing~~placing a thermal barrier between the body of the waveguide 103 and the bulb~~. Alternatively~~ 107. In one alternative embodiment, the outer wall 109 ~~includes~~acts as a thermal barrier by comprising a material with low thermal conductivity~~,~~ such as ~~an NZP ($NaZr_2(PO_4)_3$) ceramic, which acts as~~NZP. Other suitable material for a thermal barrier may also be used.

[0044] ~~[0044] **FIGs**~~FIGS. 3A and 3B illustrate an alternative embodiment of a DWIPL 300 wherein a vacuum gap acts as a thermal barrier. As shown in FIG. 3A, ~~**DWIPL 300** includes a self-enclosed~~the bulb 313 of the DWIPL 300 is disposed within a ~~lamp chamber~~bulb cavity 315 ~~which~~and is separated from ~~body **312** of a~~the waveguide 311 by a ~~vacuum~~ gap ~~**317** whose~~317, the thickness ~~is dependent upon~~of which preferably varies depending upon the microwave propagation characteristics and ~~the material strengths of waveguide body **312** and~~material strength of the material used for the body of the waveguide 311 and the bulb 313. The gap 317 is preferably a vacuum~~minimizes~~, minimizing heat transfer between the bulb 313 and the waveguide~~.~~ 311.

[0045] ~~[0045]~~ FIG. 3B illustrates a magnified view of the bulb 313, ~~chamber **315**~~bulb cavity 315, and vacuum gap ~~**317**.~~317 for the DWIPL 300. The boundaries of the vacuum gap 317 are formed by the waveguide 311, a bulb support ~~structure~~ 319, and the bulb 313. ~~Support structure **319** is~~The bulb support 319 may be sealed to the waveguide ~~and extends~~311, the support 319 extending over the edges of ~~chamber **315**. The support structure includes~~the bulb cavity 315 and comprising a material ~~having~~such as alumina

that preferably has high thermal conductivity~~, such as alumina,~~ to help dissipate heat from the bulb~~.~~ 313.

[0046] ~~[0046]~~ Embedded in the support~~ structure~~ 319 is an access seal 321 ~~which maintains~~for establishing a vacuum within the gap 317 when the bulb~~ envelope~~ 313 is in place. ~~Preferably, the~~The bulb 313 is preferably supported by and hermetically sealed to the bulb support~~ structure~~ 319. Once a vacuum is established in the gap 317, heat ~~transfer~~transfers between the bulb 313 and the waveguide ~~is~~311 are preferably substantially reduced.

[0047] ~~[0047] Preferably,~~Embodiments of the DWIPLs ~~**101, 200, 220 and 300**~~thus far described preferably operate at a microwave frequency in the range of~~ about~~ 0.5 ~~to~~- 10 GHz. The operating frequency ~~is preselected so as to excite~~preferably excites one or more resonant modes supported by the size and shape of the waveguide, thereby establishing one or more electric field maxima within the waveguide. When used as a resonant cavity, at least one dimension of the waveguide is preferably an integer number of half-wavelengths~~.~~ long.

[0048] ~~[0048] **FIGs. 4A, 4B and 4C** schematically~~FIGS. 4A-C illustrate three alternative embodiments of DWIPLs 410, 420, ~~**430**, each~~430 operating in ~~a different resonant mode. It is to be understood that each of these figures represents DWIPL **101**, DWIPL **200**, DWIPL **220** or DWIPL **300** operating in the respective resonant mode depicted. Referring to **FIG. 4A**,~~different resonant modes. FIG. 4A illustrates a DWIPL 410 ~~operates~~operating in a first resonant mode 411 where ~~the length of~~ one axis of a rectangular prism-shaped waveguide 417 has a length that is one-half the wavelength of the microwave energy used. ~~In~~ FIG. 4B~~,~~ illustrates a DWIPL 420 ~~operates~~operating in a ~~second~~ resonant mode 421 where ~~the length of~~ one axis of a rectangular prism-shaped waveguide 427 ~~equals~~has a length that is equal to one wavelength of the microwave ~~wavelength~~energy used. ~~In~~ FIG. 4C~~,~~ illustrates a DWIPL 430 ~~operates~~operating in a~~ third~~ resonant mode 431 where ~~the length of~~ one axis of a rectangular prism-shaped waveguide 437 ~~is three-halves the microwave wavelength. DWIPL **430** includes first and second microwave probes **433, 434** which supply energy to the waveguide. The probes may be coupled to a single microwave source or individually to separate sources. DWIPLs **410**,~~

~~420, 430 further include, respectively, a bulb cavity 415, 425, 435.~~ has a length that is 1½ wavelengths of the microwave energy used.

[0049] ~~[0049] In DWIPLs 410, 420, 430, bulb cavities 415, 425, 435, respectively, and probes~~ In each of the DWIPLs and corresponding modes depicted in FIGS. 4A-C, and for DWIPLs operating at any higher modes, the bulb cavity 415, 425, 435 and the feed(s) 413, 423, ~~and (~~433, 434~~), respectively,~~ are preferably positioned with respect to ~~waveguides~~ the waveguide 417, 427, ~~437, respectively,~~437 at locations where the electric fields are at an operational maximum. However, the bulb cavity and ~~probe(s)~~the feed do not necessarily have to lie in the same plane.

[0050] FIG. 4C illustrates an additional embodiment of a DWIPL 430 wherein two feeds 433, 434 are used to supply energy to the waveguide 437. The two feeds 433, 434 may be coupled to a single microwave source or multiple sources (not shown).

[0051] ~~[0050] FIG. 4D schematically illustrates a DWIPL 440 wherein a single microwave probe 443 provides energy to a~~FIG. 4D illustrates another embodiment wherein a single energy feed 443 supplies energy into the waveguide 447 having ~~first and second~~multiple bulb cavities ~~445, 446,~~415, 416, each positioned with respect to the waveguide 447 at locations where the electric field is at a maximum. ~~It is to be understood that FIG. 4D represents DWIPL 101, DWIPL 200, DWIPL 220 or DWIPL 300 operating in the resonant mode depicted, but with the DWIPL modified to include two bulb cavities.~~

[0052] ~~[0051] FIGs. 5A, 5B and 5C schematically~~FIGS. 5A-C illustrate ~~three~~ DWIPLs 510, 520, 530 ~~each~~ having ~~a~~ cylindrical prism-shaped ~~waveguide~~waveguides 517, 527, ~~537, respectively, and operating in a different resonant mode. It is to be understood that each of these figures represents DWIPL 101, DWIPL 200, DWIPL 220 or DWIPL 300 operating in the respective resonant mode depicted, but with the DWIPL modified to have a cylindrical waveguide. In each DWIPL~~537. In the embodiments depicted in FIGS. 5A-C, the height of the cylinder is preferably less than its diameter, ~~and~~ the diameter ~~is~~preferably being close to an integer multiple of the lowest order half-wavelength of energy that can resonate within the waveguide~~.~~ 517, 527, 537. Placing ~~these~~such a dimensional ~~constraints~~restriction on the cylinder results in the lowest resonant mode being independent of ~~cylinder~~the height ~~so that~~of the cylinder. The

diameter of the cylinder thereby dictates the fundamental mode of the energy within the waveguide~~. Cylinder~~ 517, 527, 537. The height of the cylinder can ~~thus~~therefore be optimized for other requirements such as size and heat dissipation. In FIG. 5A, ~~a microwave probe~~ the feed 513 is preferably positioned directly ~~opposed to~~opposite the bulb cavity 515 ~~where~~and the zeroeth order Bessel mode 511 is ~~a maximum. In **FIG. 5B**, cylindrical waveguide **527** has a diameter close to one wavelength long, so that the first order Bessel mode **521** is excited. Probe **523** is positioned at the field maximum and is diagonally opposed to bulb cavity **525**. In **FIG. 5C**, cylindrical waveguide **537** has a diameter close to three half-wavelengths long so that there are two electric field maxima at which are positioned probes **533**, **534** which provide energy to the waveguide. Bulb cavity **535** is disposed symmetrically between the two probes. Generally, in a DWIPL having a cylinder-shaped waveguide the bulb cavity and probe(s) are preferably positioned with respect to the waveguide at locations where the electric field is a maximum.~~preferably excited.

[0053] Other modes may also be excited within a cylindrical prism-shaped waveguide. For example, FIG. 5B illustrates a DWIPL 520 operating in a resonant mode where the cylinder 527 has a diameter that is preferably close to one wavelength of the microwave energy used.

[0054] As another example, FIG. 5C illustrates a DWIPL 520 operating in a resonant mode where the cylinder 537 has a diameter that is preferably close to ½ wavelengths of the microwave energy used. FIG. 5C additionally illustrates an embodiment of a DWIPL 530 whereby two feeds 533, 534 are used to supply energy to the cylinder-shaped waveguide 537. As with other embodiments of the DWIPL, in a DWIPL having a cylinder-shaped waveguide, the bulb cavity 515, 525, 535 and the feed(s) 513, 523, 533, 534 are preferably positioned with respect to the waveguide 517, 527, 537 at locations where the electric field is at a maximum.

[0055] ~~[0052] A~~Using a dielectric waveguide ~~provides~~has several distinct advantages. ~~Firstly~~First, as discussed above, the waveguide ~~body can~~may be used to help dissipate the heat generated in the bulb. ~~Secondly~~Second, higher power densities ~~can~~may be achieved within a dielectric waveguide than are possible in the plasma lamps with air cavities ~~such as those in present use. Depending~~that are currently used in the art. The energy density

of a dielectric waveguide is greater, depending on the dielectric constant of the material used for the waveguide~~ body, the energy density of a dielectric waveguide will be somewhat or substantially greater~~, than the energy density ~~in~~of an air cavity ~~waveguide of similiar dimensions in a~~ plasma lamp~~ of the related art~~.

[0056] ~~[0053]~~ Referring ~~again~~back to the DWIPL 101 of FIG. 1, high resonant energy within the waveguide ~~103 of DWIPL 101,~~103, corresponding to a high ~~Q~~-value ~~in the waveguide~~for Q (where Q is the ratio of the operating frequency to the frequency width of the resonance)~~,~~ for the waveguide results in a high evanescent leakage of microwave energy into ~~chamber~~ the bulb cavity 105. High leakage ~~into~~in the ~~chamber~~bulb cavity 105 leads to the quasi-static breakdown of the noble gas within the envelope 127, ~~thereby~~thus generating the first free electrons. The oscillating energy of the free electrons scales as ~~Iλ~~$I\lambda^2$, where ~~I~~I is the circulating intensity of the microwave energy and ~~λ~~λ is the wavelength of that energy. ~~Thus~~Therefore, the higher the microwave energy, the greater is the oscillating energy of the free electrons. By making the oscillating energy greater than the ionization potential of the gas, electron-neutral collisions result in efficient build-up of plasma density.

[0057] ~~[0054]~~ Once ~~a~~the plasma is formed in the DWIPL ~~101~~ and the incoming power is absorbed, the waveguide's Q- value drops due to the conductivity and absorption properties of the plasma. The drop in the Q- value is generally due to a change in the impedance of the waveguide. After plasma formation, the presence of the plasma in the ~~chamber~~cavity makes the ~~chamber~~bulb cavity absorptive to the resonant energy, thus changing the ~~waveguide~~overall impedance of the waveguide. This change in impedance is effectively a reduction in the overall reflectivity of the waveguide. ~~By~~Therefore, by matching the reflectivity of the ~~probe to be~~feed close to the reduced reflectivity of the waveguide, a sufficiently high Q value may be obtained even after the plasma formation to sustain the plasma. Consequently, a relatively low net reflection back into the energy source ~~is~~may be realized.

[0058] ~~[0055]~~ Much of the energy absorbed by the plasma eventually appears as heat, such that the ~~bulb~~ temperature of the lamp may approach 1000~~º~~ °C. When the waveguide is also used as a heat sink, as previously described, the dimensions of the waveguide may change due to its coefficient of thermal expansion. ~~If~~Under such circumstances, when

the waveguide expands, the microwave frequency that ~~will resonate~~resonates within the waveguide changes and resonance is lost. In order for resonance to be maintained, the waveguide ~~must have~~preferably has at least one dimension equal to an integer multiple of the half- wavelength ~~of the microwaves~~microwave frequency being generated by the microwave source ~~115.~~.

[0059] ~~[0056] A DWIPL~~One preferred embodiment of a DWIPL that compensates for ~~such dimensional changes includes a waveguide having a body consisting essentially of a solid~~this change in dimensions employs a waveguide comprising a dielectric material ~~with~~having a temperature coefficient for ~~its~~the refractive index that is approximately equal and opposite in sign to its temperature coefficient ~~of~~for thermal expansion. ~~Dimensional changes~~Using such a material, a change in dimensions due to thermal heating ~~are offset by a~~offsets the change in refractive index, ~~thus decreasing the possibility that resonance will~~minimizing the potential that the resonant mode of the cavity would be interrupted. Such materials include ~~titanates. Alternatively,~~Titanates. A second embodiment that compensates for dimensional changes due to ~~heating may be compensated for by~~heat comprises physically tapering the walls of the waveguide in a predetermined manner.

[0060] ~~[0057] FIG. 6~~In another preferred embodiment, schematically ~~shows~~shown in FIG. 6, a DWIPL 610 may be operated in a dielectric resonant oscillator mode ~~wherein~~. In this mode, first and second microwave ~~probes~~feeds 613, 615 are coupled between ~~a~~the dielectric waveguide 611, which may be of any shape previously discussed, and ~~a~~the microwave energy source 617. ~~Source~~ The energy source 617 is preferably broadband with a high gain and high ~~output~~ power~~,~~ output and ~~is~~ capable of driving ~~the~~ plasma to emission. ~~DWIPL 610 further includes a bulb cavity 619.~~

[0061] The first feed 613 may generally operate as described above in other embodiments. The second feed 615 may probe the waveguide 611 to sample the field (including the amplitude and phase information contained therein) present and provide its sample as feedback to an input of the energy source 617 or amplifier. In probing the waveguide 611, the second feed 615 also preferably acts to filter out stray frequencies, leaving only the resonant frequency within the waveguide 611.

[0062] ~~[0058] Probe 613 generally operates as described for the other embodiments disclosed herein. Probe 615 probes the waveguide 611 to instantaneously sample the field (including amplitude and phase information contained therein), and provides the sampled field information via a feedback means 612 to an input 617A of energy source 617 or to a separate amplifier. In probing the waveguide, probe 615 also preferably acts to filter out stray frequencies, leaving only the resonant frequency within the waveguide. Preferably, probes 613,~~ In this embodiment, the first feed 613, second feed, 615 and bulb cavity 619 are each preferably positioned with respect to the waveguide 611 at locations where the electric field is at a maximum. Using the ~~sampling information provided by probe~~second feed 615, the energy source 617 amplifies the resonant energy within the waveguide~~.~~ 611. The source 617 thereby adjusts the frequency of its output ~~frequency to dynamically~~to maintain one or more resonant modes in the waveguide~~.~~ 611. The complete configuration thus forms a resonant oscillator. In this manner, automatic compensation may be realized for frequency shifts due to plasma formation and thermal changes in ~~waveguide dimensions~~dimension and the dielectric constant ~~due to thermal effects, enabling continuous operation of the lamp~~.

[0063] ~~[0059]~~ The dielectric resonant oscillator mode also enables the DWIPL 610 to have an immediate re-strike ~~(i.e., re-ignition)~~ capability after being turned off. As previously discussed, the resonant frequency of the waveguide 611 may change due to thermal expansion ~~and/~~or changes in the dielectric constant caused by heat generated during operation. ~~Furthermore, the resonant frequency depends upon the state of the plasma.~~ When the DWIPL 610 is ~~shut down, the light-emitting plasma extinguishes and~~shutdown, heat is slowly dissipated ~~resulting in~~, causing instantaneous changes in the resonant frequency of the waveguide~~.~~ 611.

[0064] ~~[0060]~~ However, as indicated above, in the resonant oscillator mode the energy source 617 automatically compensates for changes in the resonant frequency of the waveguide 611. Therefore, regardless of the startup characteristics of the waveguide~~,~~ 611, and providing that the energy source 617 has the requisite bandwidth, the energy source 617 will automatically compensate to achieve resonance within the waveguide~~.~~ 611. ~~Thus, the~~The energy source immediately provides power to the DWIPL at the optimum plasma-~~-~~forming frequency.

[0065] ~~[0061]~~ While ~~several~~ embodiments ~~for carrying out the~~and advantages of this invention have been shown and described, it ~~will~~would be apparent to those skilled in the art that ~~additional~~many more modifications are possible without departing from the inventive concepts ~~detailed herein. It is to be understood, therefore, there is no intention to limit the invention to the particular embodiments disclosed. On the contrary, it is intended that the invention cover all modifications, equivalences and alternative constructions falling within the spirit and scope of the invention as expressed in~~herein. The invention, therefore, is not to be restricted except in the spirit of the appended claims.

ABSTRACT~~ OF THE DISCLOSURE~~

~~[0107] A dielectric waveguide integrated plasma lamp (DWIPL) with a body consisting essentially of at least one dielectric material having a dielectric constant greater than approximately 2, and having a shape and dimensions such that the body resonates in at least one resonant mode when microwave energy of an appropriate frequency is coupled into the body. A bulb positioned in at least one lamp chamber in the body contains a gas-fill which when receiving energy from the resonating body forms a light-emitting plasma.~~A dielectric waveguide integrated plasma lamp is disclosed for powering a small and bright bulb with a diameter of a few millimeters. The lamp is contained within a high dielectric constant material which guides the microwaves to the bulb, provides heat isolation to the drive circuit, contains the microwaves, provides structural stability and ease of manufacturing and allows efficient energy coupling to the bulb when used as a dielectric resonant oscillator.